Structural Engineering and Mechanics, *Vol. 49, No. 3 (2014) 311-327*
DOI: http://dx.doi.org/10.12989/sem.2014.49.3.311

Safety analysis and design of full balanced hoist vertical shiplifts

Lekang Liao*

Chang Jiang Institute of Survey Planning Design and Research, Wuhan 4300l0, China

(Received August 26, 2012, Revised November 13, 2013, Accepted December 9, 2013)

Abstract. The safety relating to leakage of water and pitch instability of ship chambers of the full balanced hoist vertical shiplifts has been the focus of adoption of the type of vertical shiplifts. This paper aims to remove the doubts through theoretical and engineering researches. The leakage and pitch stability of ship chambers of full balanced hoist vertical ship lifts are investigated on the basis of theoretical analysis and exploration of engineering measures. Regarding the issue of leakage of ship chambers, a mathematical model on leaking process is built and corresponding formula and coping measures are obtained which can be applied in control program of ship lifts by linking with monitoring. The concept of safety grade is put forward to seek the best technical and economic index and the corresponding technical measures are for different grades of ship lift is suggested. For the issue of pitch instability, a methodology of combining theoretical deduction and summary of achievements of design and operation of the type of the full balanced hoist shiplifts is adopted, and the formula for design about pitch stability of ship chambers is derived.

Keywords: full balanced hoist vertical shiplift; ship chamber; safety; leakage; pitch stability; critical leakage time; critical pitch angle; critical longitudinal centre distance of a hoist for dynamic pitch stability; safety coefficient for pitch dynamic stability

1. Introduction

1990s and 2000s have been seeing rapid development of vertical shiplifts in China, due to their advantages in the navigation of ships in high dams over the locks (Niu and Song 2007). There are four types of vertical shiplifts with counterweight in China, full balanced hoist vertical shiplifts , full balanced rack and pinion vertical shiplifts, launching hoist vertical shiplifts, and hydraulic vertical shiplifts among which the type of full balanced hoist vertical shiplifts is the best in terms of economics, operational conditions , the adaptation of deformation of the civil bearing structures, and applicability to large range of tonnage of ships and lift height, without any difficulty in manufacturing of pinions and gears appearing in the full balanced rack and pinion vertical shiplifts, launching hoist vertical shiplifts. Full balanced hoist vertical shiplifts have been developed in China since 1984 when feasibility research of the Three Gorges hydraulic project begun to carry on, in which the Three Gorges shiplift was designed on the basis of studying the Strepy Thieu Shiplift (Schinkel 2001) in Belgium in 1980s. After investigation of shiplifts in

*Corresponding author, Senior Engineer, E-mail: liaolekang@yahoo.com.cn

http://www.techno-press.org/?journal=sem&subpage=8 ISSN: 1225-4568 (Print), 1598-6217 (Online)

Europe and analysis of the temporal manufacture ability of the machinery, designers of the Three Gorges shiplift decided to adopt the type of the Strepy shiplift. As a precaution, the design department in connection with universities, institutions and large scale manufacturers in China carried out dozens of National Science and technology research programs in more than 15 years, and took the GeHeyang shiplifts and the ShuiKou shiplift as testing shiplifts for accumulation of experiences of design and manufacture. The issue of safety of full balanced hoist shiplifts was originated by an event occurred in 1994 (Chen *et al.* 1996). The ship chamber of the physical model of the ShuiKou shiplift, the first built full balanced hoist vertical shiplift in China (Wang and Hu 2008), overturned when the leakage test was being carried on. Researchers explained convincingly the cause of the incident in the view of statics (Chen *et al.* 1996), saying that the turnover had been caused by losing of water in the ship chamber leading up to disappearing of tension of some hoist wire ropes. The result of physical model test and the article is a valuable achievement for full balanced hoist ship lifts, especially for the ShuiKou shiplift because potential security hazard was discovered and the design was improved according to the analysis result. But this event unfortunately caused the doubt about safety relating to leakage, and further, the suspect of dynamical pitch stability, of the type of full balanced hoist vertical shiplifts across the circles of engineering and science in China. It was just for this reason, it is decided in 2003 that the type of the Three gorges shiplift , the largest shiplift in the world, changed from the type of full balanced hoist vertical shiplift to the type of the full balanced rack and pinion vertical shiplifts,and the way of joint design of China and German was adopted (Akkermann *et al.* 2009), (Niu *et al.* 2011). Since then the research of issues of water leaking and pitch stability of ship chambers , as well as the technical measures to improve the safety in design, have been performed by designers and the scholars (Liao and Shi 1996a, b), (Cheng *et al.* 2005), (Li 2006). Leakage and instability have never taken place among the constructed full balanced hoist shiplifts during operation and debugging.

In this paper, two issues relating to safety of full balanced hoist shiplifts are discussed: 1) water leakage, the quantitative analysis and safety measures, and 2) the pitch stability of ship chambers, the analysis of stability and the corresponding design method.

2. Safety relating to water leakage of ship chambers

Leakage of ship chambers of shiplifts has not been occurred in the history of shiplift construction in the world (Tang 2002). The German shiplift designers took the leakage of a ship chamber as a design case with their precaution. So they adopted the type of the full balanced rack and pinion vertical shiplifts in the designs of the old Niederfinow shiplift (Wasser-und Schifffahrtsdirektion Ost 2005), the new Niederfinow shiplift (Herwig 2010) and the Lunaburg shiplift (Schinkel 2001), each of which has a safety mechanism to lock the ship chamber when water is leaking. This type of shiplifts is undoubtedly safe, but they are very complicated in systems and structures and very expensive.

On the other hand, Belgium Strepy Thieu shiplift designers have different opinions on the leakage accident. They designed Belgium Strepy shiplift with the type of full balanced hoist shiplift which did not set the safety mechanism. But the shiplift have enough hoist force to ensure that before the weight of lost water arrived 9450kN, the hoist has capacity to drive ship chamber to lift. This measure can ensure the safety of shiplifts when leakage speed or leaking area are beneath some certain value.

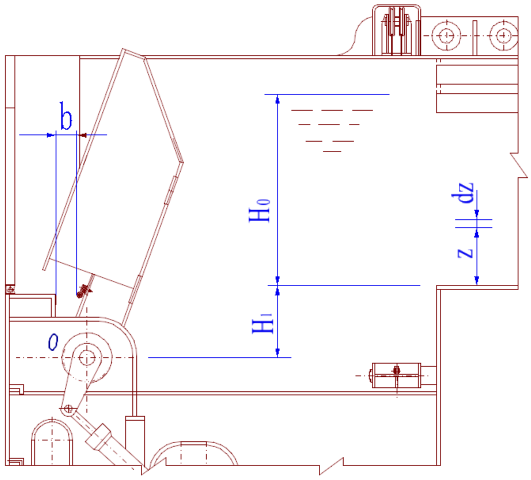

Fig. 1 Sketch of gap in bottom of the gate

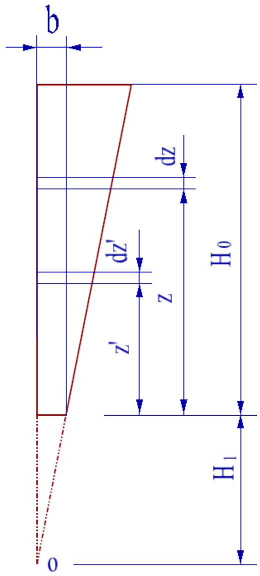

Fig. 2 Sketch for calculation of the gap

Should we thoroughly accept the concepts of German designers or of Belgium designers? If not, how should we treat the leakage accident? This issue is expounded in the following three parts.

2.1 Analysis of leaking process

Three cases can be imagined that cause water leaking in a ship chamber. The first is the cracks of welded seams of the structure of a ship chamber. The second is the torn of water seals on the gates of a ship chamber. The third is the block of gates of a ship chamber, which is worst and most possible case among the three cases. Here this paper only analyzes the blocking of the flap gate. The case occurs when a foreign object blocks the flap gate forming the gap between the seals in a flap gate and the bed plats in the bottom and two sides.

Fig. 1 signifies the water leakage in the bottom of the flap with the breadth and length of the gap being respectively b and B. The leakage micro-volume in the bottom gap during period of dt is calculated according to the formula for thin wall orifice flow

$$dV_1 = \mu A\sqrt{2gz}dt = -BLdz \tag{1}$$

Where μ=0. 6 is flow coefficient, A the area of slot of leakage; g the acceleration of gravity; z the distance from micro-value of water with thickness dz to the bottom of the ship chamber, B the length of the slot in the bottom; L the length of the ship chamber. H_0 is the design water depth; H_1 the distance from the bottom of water from the hinge point of the flap gate. The leakage micro-volume in gaps in the two sides between the seals and bed plats is more complicated to calculate as the gaps change in breadth as shown in Fig. 2. The formula (1) thus can not be directly applied. In Fig. 2, O is the hinge point of the flap gat, b the gap in the bottom of the gate. In the depth z' the thickness of dz' is treated as a constant, so the formula of thin wall orifice flow is applied. In the depth z' the leakage micro-area in horizontal plane is

$$dA(z') = (1 + \frac{z'}{H_1})bdz'$$

The leakage micro-volume in one size is

$$dV_2 = (\int_0^z \mu\sqrt{2g(z-z')}dA(z')dt = (\int_0^z \mu b(1+\frac{z'}{H_1})\sqrt{2g(z-z')}dz')dt$$

$$= (\int_0^z \mu b(1+\frac{z'}{H_1})\sqrt{2g(z-z')}dz')dt = \mu b(\frac{2}{3}+\frac{4z}{15H_1})\sqrt{2gz^3}dt \quad (2)$$

The sum of the block of a flap gate of the ship chamber leakage micro-volume is

$$dV = dV_1 + 2dV$$

$$= (\mu Bb\sqrt{2gz} + \mu b(\frac{4}{3}+\frac{8z}{15H_1})\sqrt{2gz^3})dt = -BLdz \quad (3)$$

Formula (3) can be derived to following form

$$dt = -\frac{BLdz}{\mu Bb\sqrt{2gz} + \mu b(\frac{4}{3}+\frac{8z}{15H_1})\sqrt{2gz^3}} \quad (4)$$

Let H_0 be the water depth of water when leakage begins and H the water depth after time t, then

$$t = \int_H^{H_0} \frac{dz}{\mu\frac{b}{L}\sqrt{2gz} + \mu\frac{b}{L}(\frac{4}{3B}+\frac{8z}{15BH_1})\sqrt{2gz^3}} \quad (5)$$

According to the research results of the article (Zhu *et al.* 2002), when leakage weight surpasses 90% of the weight of torque counterweight, the ship chamber will loss pitch stability. Let H_c be corresponding remaining water depth, t_c be corresponding time, and let $\gamma=b/L$ be relative leakage width, and

$$I_1 = \int_{H_c}^{H_0} \frac{dz}{\mu\sqrt{2gz} + \mu(\frac{4}{3B}+\frac{8z}{15BH_1})\sqrt{2gz^3}} \quad (6)$$

which is a constant and is calculated by numerical computation using Mathematica. Then

$$t_c = \frac{I_1}{\gamma} \quad (7)$$

Fig. 3 shows the relation curves between the $\gamma=b/L$ and the critical leaking time of GaoBazhou, Penshui, TingZikou and the Three Gorges shiplifts, which represent the four typical tonnages of ships for the shiplifts constructed and under construction. The ratio of 0.9 time weight of counterweight to the weight of water in the ship chambers are respectively 0.535, 0.467, 0.589 and

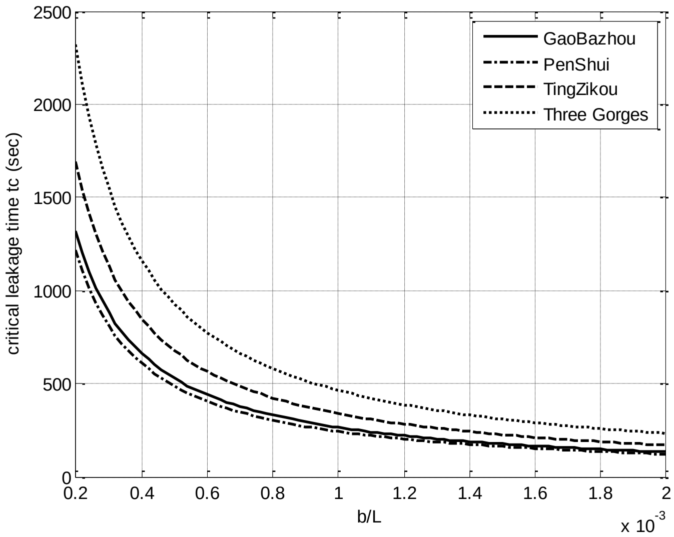

Fig. 3 the variation curve of critical leaking time via the ration *b/L*

0.656. So the ratios of weight of counterweight to the weight of water mainly decide the shape of relation curves between $\gamma=b/L$ and the critical leakage time. The allowed bottom gap can be determined by Fig. 3 and the maximum lift time. For example, the maximum lift time of the Three Gorges shiplifts is 565 seconds. Provided that a hoist lifts the ship chamber from the bottom of the chamber to the upper butting elevation, the bottom gap of the flap gate should be less than 106mm. It can be seen that increasing the weight of torque counterweight is very important to enhance the ability to cope with leakage.

For the first and second case of leakage, the corresponding formula similar to (6) and (7) are written as follows. When cracks of welded seams of the structure of a ship chamber exist, the relation between the leakage area *A* and the critical leakage time $t_{c,}$ is

$$t_s = \frac{BL(\sqrt{2H_0} - \sqrt{2H_s})}{\mu A\sqrt{g}} \tag{8}$$

When all seals are torn, even disappear in worst case, the relation between the relative leakage width $\gamma=b/L$ and the critical leakage time t_c is as following

$$t_s = \frac{I_2}{\gamma} \tag{9}$$

Where

$$I_2 = \sqrt{\frac{3B}{2\mu^2 g}} tg^{-1}(\sqrt{\frac{4H_0}{3B}}) - tg^{-1}(\sqrt{\frac{4H}{3B}}) \tag{10}$$

The corresponding relation curves between the t_s and A or t_s and $\gamma=b/L$ can be drawn according to (8), (9) and (10).

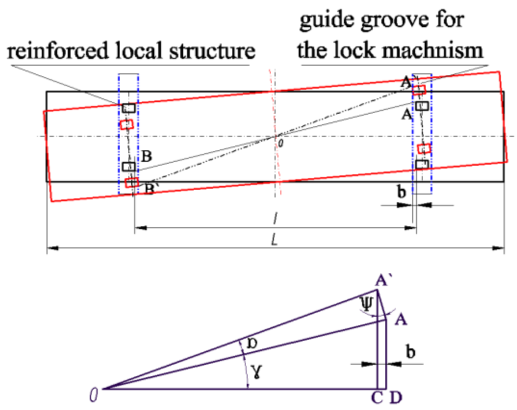

Fig. 4 Sketch of the state of block of a ship chamber

Enough torque counterweight is only a prerequisite for shiplifts to operate under the leakage of ship chambers. The load of the hoist will possibly exceed its driving force in the process of leakage. In this case, a possible solution is to let safety brakes brake in groups or brake step by step. In this way, the load of hoist will not operate beyond the maximum driving force, as braking torque of the safety brakes is determined according to the torque on the shafts of drums caused by the weight of the torque counterweights.

In order to increase the capacity for coping with leakage, the allowable water level differences can be reasonably raised, and keep it a positive value. Then the critical leakage time and corresponding allowed leakage gap can be enlarged. The positive water level difference also keeps the load of the hoist unidirectional, which increases the capacity of the load-bearing capacity of reduction gears by 43% comparing to the bidirectional load of the hoist.

The formulas (6)~(10) and the corresponding measures can be brought into the control programs of the full balanced shiplifts to judge the velocity of leakage and select automatically the corresponding measures regulated in the program.

2.2 Safety status of equipments in instability case of the ship chamber

From the above analysis, it is known that, for a shiplift with certain weight of torque counterweight, the ship chamber will inevitably instable when the gap of the bottom of the flap gate exceeds the certain value. In this moment, the ship chamber tilts longitudinally for an angle and then is blocked and borne on the guide grooves or guide rails for the whole journey lock mechanisms at the reinforced local structures of the ship chamber, as the clearances between the guide grooves and the reinforced local structures disappear. The hoist will be protected by safety brakes when they fully brake. The maximum stress of the reinforced local structures may exceed the allowable stress but integral safety of the ship chamber can be assured. If there is certain depth of water in the ship chamber which causes overturning moment on the ship chamber, there will be large supporting forces at the reinforced local structures of the ship chamber. Fig. 4 shows the bearing status of the ship chamber and the sketch for calculation of the supporting forces at the local structures. The black solid lines represent the normal state of a ship chamber; and the red solid lines represent the accidental state of which the ship chamber is blocked at the locations *A’* and *B’* of guiding grooves, showing in blue two-dot chain lines of s ship chamber. Let *b* be the clearance between the guide grooves and local structures, α the pitch angle, $OD=l/2$, $OA=OA'=l_1/2$, $AA'=x$, and γ the geometrical parameters of the ship chamber. Then

$$\frac{x}{l_1} = \sin\frac{\alpha}{2} \approx \frac{\alpha}{2}$$

$$x = \frac{\alpha l_1}{2} \tag{11}$$

$$\frac{b}{x} = \sin\psi \approx \psi \tag{12}$$

$$\cos\gamma = \frac{l_1}{l} \tag{13}$$

there is a relationship among α, ψ and γ as the following

$$\psi - \gamma - \frac{\alpha}{2} = 0 \tag{14}$$

Substituting (11) and (11) into (14), we get

$$\alpha^2 + 2\gamma\alpha - \frac{4b}{l_1} = 0 \tag{15}$$

By choice the positive root of the algebraic equation, we get

$$\alpha = \sqrt{\gamma^2 + \frac{4b}{l_1}} - \gamma \tag{16}$$

The overturning moment of the remaining water, if there is a little, on the ship chamber is

$$M = \frac{1}{12}\rho g B L^3 \alpha \tag{17}$$

The supporting moment is supplied by the supporting forces of guide groove on the local structures. According to moment balance of the ship chamber, the normal force and friction force applied on a single local structure are derived:

$$\text{Normal force:} \quad N = \frac{M}{2(l\mu + a)} = \frac{BL^3\alpha}{24(lf + a)} \tag{18}$$

$$\text{Friction force:} \quad F = \mu N = \frac{\mu B L^3 \alpha}{24(l\mu + a)} \tag{19}$$

As an example, the stress of the Three Gorges ship chambers is computed applying the FEM method under the case of leakage, in which the weight of the ship chamber and the tension of the wire ropes, which are directly collected to the gravity counter weight, are also considered besides the water pressure. Provided that the weight of remaining water in the ship chamber is 28000kN, the clearance between the reinforced local structures and guide grooves of the whole journey lock mechanisms is 50mm, which is much larger than the value determined in design. The FEM computation result shows that the stress exceeds the yield limit of steel material only in local parts. A conclusion can be drawn that hoists equipment and ship chambers are basically safe for leakage accidents.

2.3 Grading of safety for coping with leakage and the corresponding measures

2.3.1 Grading of safety for coping with leakage

The optimum design of the Three Gorges hoist vertical shiplift is well in coping with leakage of water in the ship chamber, as the shiplift has to reach the same safety criteria as the type of the rack and pinion vertical shiplift, that the ship chamber can be locked even in the case of empty of the ship chamber, for the purpose of type comparing and adaptation of the shiplift. Although the optimum design was not put in practice finally, the design concepts have been applied in many following full balanced vertical shiplifts.

From the analysis of section 2.2, it is known that the leakage is not a catastrophic accident for the type of full balanced vertical shiplifts if enough attention is paid. At present in China, as the rapid development of constructions of railway and aviation, shiplifts are basically navigation facilities serving cargo ships. In this situation, should we satisfy requirement of completely lock in the case of emptiness of vertical shiplifts? It is suggest that the designers should take safety measures against leakage as far as possible, including the lock in the case of emptiness of vertical shiplifts. On the other hand, however, it should be allowed for the designers of shiplifts to seek the optimization equilibrium point between the safety, economy and applicability, just like the design of other transportation facilities, such as bridges, elevators, vehicles even planes. So it is necessary to establish different safety criteria according to the tonnage and the sorts of ships which shiplifts serve. For shiplifts serving cargo ships with tonnage less than or equals to 500t, it is reasonable to allow that the demand of complete lock of the ship chambers in the case of emptiness of the ship chambers may not be satisfied, but other safety measures must be taken according to specific conditions. This criteria is called *the common safety criteria*. For the shiplifts that serve passenger ships or cargo and passenger ships, or any sorts of ships with tonnage more than 500t, the demand of complete lock of the ship chambers in the case of emptiness of the ship chambers should be satisfied, in order to avoid the pecuniary losses and psychological panic of the passengers caused by damage of the ship chambers and suspension of navigation. This criteria is called *special safety criteria*.

2.3.2 Safety measures for coping with leakage

For the full balanced vertical shiplifts of common safety criteria, the designers can take following safety measures to cope with leakage which are less expensive if they do not want to or can not satisfy the demand of complete lock in the case of emptiness of the ship chambers:

i. to perfect the detection of operation of the chamber gates, and the control program of shiplifts for handling leakage accident, including detecting the velocity of leakage, selecting and carrying out the measures automatically , and interlocking between the chamber gates and the clearance seal mechanisms of chambers ;

ii. to set the foreign body removing mechanism;

iii. to set reinforced local structures to support the pitch instable ship chambers;

iv. to set the gates for accident and inspection and repair in front of the flap gates of ship

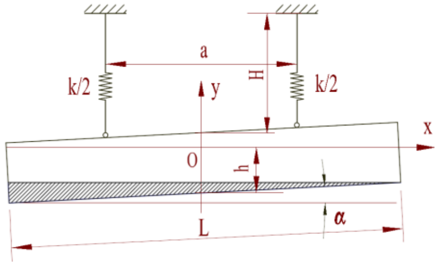

Fig. 5 Model diagram for static analysis of pitch stability

chambers, in order to stop the leakage in case of block in the flap gates.

v. to set the weight of torque counterweight as much as possible , and to enhance appropriately the allowable water depth difference and keep it positive. This increases the critical leakage time so that hoists can lift the leaking ship chambers before turnover.

For the full balanced vertical shiplifts of special safety criteria, besides the measures for the shiplifts of the common safety criteria, the design should satisfy the demand of complete lock in case of emptiness of the ship chambers. The following ways can accomplish it: to set the weight of torque counterweight as much as possible, or set controllable counterweight which can be braked by brakes; to increase the lock capacity, or set the special lock mechanisms for leakage.

For example, in the optimum design of the Three Gorges hoist vertical shiplift (Wu and Yu 2003), the weight of the torque counterweight is 62000kN, which can be braked, and the lock force of whole journey lock mechanism is 38000kN. The sum of them is 100000 kN, which is larger than 86700kN, the weight of water in the ship chamber. The way to cope with leakage of water in the ShuiKou full balanced hoist shiplift is to arrange 8 sets of accident lock mechanisms with general lock force 8×5000kN that larger than 39390kN (Wang and Hu 2008) ,the weight of water in the ship chamber of the ShuiKoufull balanced hoist shiplift. Only by this means, the unbalanced load caused by leakage can be borne and transferred safely to the civil structure.

From the analysis above, it can seen that the type of full balanced shiplifts is both economic and safe enough in coping with leakage of ship chambers if reasonable technical measures are taken.

3. Safety relating to pitch instability of ship chambers

In last section, the instability of ship chambers caused by leakage of ship chambers has been mentioned. But leakage is just one of the causes that result in the instability. The pitch instability caused by the layout of equipments of full balanced hoist shiplifts is more profound in theory and more practical in design. On one hand, it relates to the theory of dynamical stability, on the other hand, it relates to layout of shiplift more closely.

It is necessary to mention that the research model and results are not only for the type of full balanced hoist shiplifts, but for all types of vertical shiplifts as well.

3.1 Static analysis of pitch stability

It has been mentioned that the physical explanation of instability by leakage is that the tension

Table 1 Critical pitch angle and the corresponding level difference of the shiplifts constructed or under construction in China

parameters / shiplift name	critical pitch angle (°)	allowed maximum level difference (mm)
The first step of GeHeyan shiplifts	0.175	143
The second step of GeHeyan shiplifts	0.337	277
GaoBazhou shiplift	0.205	179
PenShui shiplift	0.0742	92
ShuiKou shiplift	0.266	330
TingZikou Shiplift	0.084	184
The second step of GouPitan shiplifts	0.511	633

of hoist wire ropes is zero so that hoist wire ropes can not supply the resistant moment against capsizing moment. Similarly, in another case, even the leakage does not take place, if the pitch angle exceeds some value, no matter how the angle arise, initial horizontal error resulted from install or dynamic pitch vibration of ship chambers, or the sum of them, the pitch stability occurs. As shown in Fig. 5, when the changes in tension of each of spring with elasticity coefficient $k/2$ exceeds their minimum tension in normal operation, which means that the tension of one of springs in Fig. 5 is zero , then pitch instability occurs.

Provided that the surface of the water in a ship chamber is horizontal, the critical pitch angle of a ship chamber for pitch instability is α_{ca}, the term for critical pitch stability is as follows

$$\frac{ka\alpha_{ca}}{4} = \frac{W_c - F_h}{2} \tag{20}$$

Where α is the longitudinal central distance of main hoists of full balanced vertical hoist shiplifts, W_c is the weight of the torque counterweight, F_h is the rated hoist force, k is the minimum elastic coefficient of all hoist wire ropes, with the ship chamber being lowest level. For rack and pinion vertical shiplifts, k is the elastic coefficient of pinion bracket that has to be computed by the numerical method. Then (20) becomes

$$\alpha_{ca} = \frac{2(W_c - F_h)}{ka} \tag{21}$$

Table 1 shows the critical pitch angle and the corresponding level difference of the shiplifts constructed or under construction.

In order to explain the conception of the stability of ship chambers, let us investigate static stability by building a simplified model as shown in Fig. 5, before carrying out dynamical stability study with more complicated models. The capsizing moment is produced by the water of the triangle area shown in the shadow area. The capsizing moment is

$$M_p = \rho\frac{1}{2}\cdot L\cdot L\alpha\times\frac{1}{6}L\cdot B = \frac{\rho L^3 B\alpha}{12} \tag{22}$$

The resistant moment against capsizing of a ship chamber is supplied by the difference of tensions between the wire ropes in two sides

$$M_{\mathrm{a}} = Ta = \mathrm{ka}^2\alpha / 4 \tag{23}$$

The term of the pitch stability is

$$M_{\mathrm{a}} > M_p \tag{24}$$

Substituting (22) and (23) into (18), the term for static pitch stability is derived

$$a > a_{cs} = \sqrt{\frac{g\rho BL^3}{3k}} \tag{25}$$

a_{cs} is called the static critical longitudinal centre distance of a hoist. Small a_{cs} means strong static pitch stability of chambers. For hoist vertical shiplifts,

$$k = \frac{EA}{n_r H} \tag{26}$$

E is the elastic model of wire ropes, A the metal area of a section of a wire rope, H the maximum suspension height of which the ship chamber is in the lowest level. So (19) becomes

$$a > a_{cs} = \sqrt{\frac{g\rho BL^3 H}{3n_r EA}} \tag{27}$$

This formula coincides very much with the result obtained by FEM numeral analysis of the pitch stability of the Three Gorges hoist vertical shiplift (Cheng *et al.* 2005). It can be seen clearly from (27) that the static stability depends on the dimensions of ship chambers, lift heights of shiplifts, and the parameters and numbers of hoist shiplifts. The static stability based on this model is the basis of ship chambers. But the formula (27) is not safe for design, as the effects of elasticity of the hoists and slosh of water surface in the ship chamber are ignored.

3.2 Dynamic analysis of pitch stability

According to operational experience of the constructed shiplifts and test analysis of hydrodynamic of water in ship chambers of physical models of shiplifts (Yang and Zeng 1992), the wave amplitudes of the water in ship chamabes during the process of lift is very small, the capsizing moment is mainly caused by the longitudinal inclination of ship chambers. So Housner theory for water slosh in rigid container with water is applied when building the hydrodynamic model of the water in ship chambers. According to Housner theory, as shown in Fig. 6, provided that there is a thin layer of water with unit water thickness, the area in shadow, the upper and lower surfaces of rigid water can rotate. Let α be the pitch angle of vibration and θ_0 the slosh angle of water surface. Considering that the longitudinal length of ship chambers is far more than water depth, the capsizing moment caused by water pressure on the flaps at the ends of the ships is ignored. The capsizing moment acted on the bottom of the bottom floor plate is (Liao and Shi 1996)

$$M = -J_s(\ddot{\theta}_0 + \ddot{a}) + C_s(a + \theta_0) \tag{28}$$

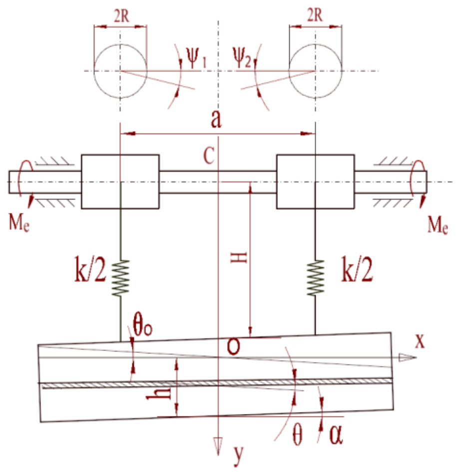

Fig. 6 coupled dynamic model of a hoist and a ship chamber

and the relation of pitch angle and the slosh angle of water surface is

$$\ddot{\theta}_0 + \frac{10gh}{L^2}\theta_0 - \ddot{a} = 0 \tag{29}$$

Where

$$J_s = \frac{\rho BhL^3}{24}, \qquad C_s = \frac{g\rho BL^3}{12} \tag{30}$$

Fig. 6 shows the coupling dynamic model of a hoist and a ship chamber. Considering the design principle of equalization of output torques of motors in electric driving systems, both the torques acted on the equivalent output shafts transferred from motor shafts of a hoist are M_e. The coupled dynamic system of a hoist and a ship chamber with water in it is described by the following differential equation group

$$J\ddot{\psi}_1 + \frac{kR}{2}(R\psi_1 - y_c - \frac{1}{2}a^a) + c(\psi_1 - \psi_2) = 0 \tag{31}$$

$$J\ddot{\psi}_2 + \frac{kR}{2}(R\psi_2 - y_c + \frac{1}{2}a^a) + c(\psi_2 - \psi_1) = 0 \tag{32}$$

$$J_2(\ddot{a} + \ddot{\theta}_0) + \frac{1}{2}ka(-R\psi_1 + y_c + \frac{1}{2}a^a) + \frac{1}{2}ka(R\psi_2 - y_c + \frac{1}{2}a^a) - c_s(a + \theta_0) = 0 \tag{33}$$

$$\ddot{\theta}_0 + \frac{10gh}{l^2}\theta_0 - \ddot{\alpha} = 0 \tag{34}$$

Where the dot above the variables means the derivatives on time, and R is the radius of drums of a hoist, J the equivalent moment of inertia about the output shaft of the hoist, c the torsional rigidity of the equivalent output shafts transferred from synchronization shaft systems, y_c the vertical displacement of the gravity centre of the ship chamber, ψ_1 and ψ_2 the rotation angles of the drums in a hoist.

3.3 The simplified term for pitch stability

In order to derive the formula that satisfies the term of pitch stability of ship chambers, the differential equation group (31)~(34) is simplified by the assumption that the surface of water in ship chambers is horizontal all along, that is, $\theta_0=0$. Let $\phi=\psi_2-\psi_1$, the differential equation group (25)~(28) can be simplified as following

$$\ddot{\phi}+c_{11}\phi+c_{12}a=0 \tag{35}$$

$$\ddot{a}+c_{22}a+c_{21}\phi=0 \tag{36}$$

Where

$$c_{11}=\left[\frac{kR_2}{2}+(\beta+2)c\right]/J \quad c_{12}=kaR/(2J) \quad c_{21}=kaR/(4(J+J_s)) \quad c_{22}=(\frac{1}{4}ka_2-c_s)/(J_2+J_s) \tag{37}$$

The differential equation group (35), (36) can be transformed to following differential equation with a single variable

$$a^{(4)}+(c_{11}+c_{22})\ddot{a}+(c_{11}c_{22}-c_{12}c_{21})a=0 \tag{38}$$

Let $\lambda=\ddot{\alpha}$ then

$$\ddot{\lambda}+(c_{11}+c_{22})\dot{\lambda}+(c_{11}c_{22}-c_{12}c_{21})\lambda=0 \tag{39}$$

The corresponding characteristic algebra equation is

$$r^2+(c_{11}+c_{22})r+(c_{11}c_{22}-c_{12}c_{21})=0 \tag{40}$$

The roots of the characteristic algebra equation is

$$r=\frac{-(c_{11}+c_{22})\pm\sqrt{(c_{11}+c_{22})^2-4(c_{11}c_{22}-c_{12}c_{21})}}{2} \tag{41}$$

According to the theory of the stability of ordinary differential equations, the term of stability of system of ordinary differential equations is that the real part of the roots of the characteristic algebra equation should be less than or equal to zero. So the stability of system of ordinary differential equations is

$$(c_{11}c_{22}-c_{12}c_{21})\geq 0 \tag{42}$$

Substituting (31) into (35), the term of pitch stability is derived

$$a\geq a_{cd}=\sqrt{(1+\frac{kR^2}{2c})\frac{g\rho BL^3}{3k}} \tag{43}$$

This formula is applicable for all types of vertical shiplifts. For the hoist vertical shiplifts, $k = n_r EA / H$, $C = 2i^2 G J_a n_a / l$

Where G is the shear modulus of elasticity of steel material, J_a the polar moment of inertial of cross section of a single longitudinal synchronization shaft, n_a the number of longitudinal synchronization shafts in the hoist, i the transmission ratio between the output shaft and synchronization shafts. For the types of rectangle and X shape synchronization shaft systems, n_a=2; for the H shape synchronization shaft systems, n_a=1; Then (36) can be written as following

$$a > a_{cd} = \sqrt{(1 + \frac{EAR^2 \ln_r}{2GJ_a H n_a i^2}) \frac{g\rho BL^3 H}{3nEA}} = \xi a_{cs} \tag{44}$$

The coefficient $\xi = \sqrt{1 + EAR^2 \ln_r / (2GJ_a H n_a i^2)}$ is called the *influence coefficient* of hoists on pitch stability of ship chambers.

3.4 Influence of slosh of water surface on pitch stability and the design formula for pitch stability of ship chambers.

Now let us return to the differential equation group (31)~(34).

Let $\phi=\psi_2-\psi_1$, $\delta=a-\theta_0$, (31)~(34) are transformed into the following differential equation group

$$J\ddot{\phi} + (\frac{kR^2}{2} + 2c)\phi + \frac{1}{2} kaRa = 0 \tag{45}$$

$$2J_s \ddot{a} + (\frac{1}{2}ka^2 - \frac{10ghJ_s}{L^2} - 2c)a + \frac{1}{2}kaR\phi + (c_s + \frac{10ghJ_s}{L^2})\delta = 0 \tag{46}$$

$$\ddot{\delta} + \frac{10gh}{l^2}(a + \delta) = 0 \tag{47}$$

The characteristic algebra equation for the differential equation group (44)~(46) is

$$c_0 r^6 + c_1 r^4 + c_2 r^2 + c_3 = 0 \tag{48}$$

let $\lambda = r^2$, it can be derived that

$$c_0 \lambda^3 + c_1 \lambda^2 + c_2 \lambda + c_3 = 0 \tag{49}$$

Where

$$c_0 = \frac{b_5}{b_6} \quad c_1 = b_5 + \frac{b_4 b_1 J}{2b_2} + \frac{b_3 b_4 L^2}{b_2} \quad c_2 = \frac{b_1 J}{L^2} - (2c_s + b_4 b_7)J + 2b_3 J_s + \frac{b_3 b_1 b_4}{4b_2 J_s} - \frac{b_4{}^2 b^6}{2}$$

$$c_3 = \frac{b_1 J}{L^2} - (2c_s + b_4 b_7)J + 2b_3 J_s + \frac{b_3 b_1 b_4}{4b_2 J_s} - \frac{b_4{}^2 b^6}{2} \quad c4 = \frac{b_3}{2J_s}(\frac{ab_4}{R} - 2b_7 b_4 - 2c_s) - \frac{b_4{}^2}{2}$$

$$b_1 = ka^2 L^2 - 20ghJ_s - 2c_s \quad b_2 = 5ghkaR \quad b_3 = (kR^2 + 4c) .$$

$$b_4 = kaR, \quad b_5 = 4\,J\,J \quad b_6 = \frac{L^2}{10gh} \quad b_7 = \frac{20ghJs}{kaRL^2} \tag{50}$$

According to the term of the stability of ordinary differential equations mentioned above and the design parameters, the critical longitudinal central distances a_{cd}' of the hoists for the stability of system of ordinary differential equation group (45~47) for the full balanced hoist vertical shiplifts constructed and under construction are computed by numerical computation method. The parameter $\eta=a_{cd}'/a_{cd}$ is defined as the influence coefficient of the slosh of the water surface. Table 2 gives the parameters relating to pitch stability. From Table 2 it can seen that the influence coefficient of hoists on pitch stability is generally not evident as the synchronization shafts are connected with second high rotational speed shaft of the reduction gears. Longer synchronization shafts may increase the effect of hoists on the pitch stability as the shafts are weaker in torsional rigidity, like ShuiKou shiplift and TingZikou Shiplift. The effect of slosh of water surface is more evident, and the influence coefficient of the slosh of the water surface is 1.24~1.593. So enough safety coefficient should be considered. In addition to the influence coefficient of slosh of the water surface, the model errors and suitable safety margin should be considered. For the sake of safety, the minimum safety coefficient for pitch stability is defined tas following

$$n = \frac{a}{a_{cd}} \tag{51}$$

The practical minimum safety coefficients are calculated according to (51) and the parameters of the shiplifts constructed or under construction. It is suggested that the minimum safety coefficient 2.20 among the forth column, which is that of the ShuiKou full balanced hoist vertical ship lift that have safely been operating in nearly ten years, is adopted as the regulated minimum design safety coefficient of pitch dynamic stability for vertical shiplifts.

So for the hoist vertical shiplifts, the design formula for pitch stability of the ship chambers is:

$$a > 2.2\sqrt{(1+\frac{EAR^2 \ln_r}{2GJ_a Hn_s i^2})\frac{g\rho BL^3 H}{3nEA}} \tag{52}$$

From (46), it can be seen that the crucial technical measures to enhance the pitch instability of

Table 2 practical and critical longitudinal distances of the hoists and practical safety coefficient for pitch stability of the shiplifts constructed or under construction in China

parameters / shiplift names	a (m)	a_{cd} (m)	n	a_{cs} (m)	ξ	a_{cd}' (m)	η
The first step of GeHeyan shiplifts	23.6	7.76	3.04	7.64	1.02	12.33	1.59
The second step of GeHeyan shiplifts	24	10.6	2.26	10.26	1.03	15.657	1.515
GaoBazhou shiplift	26	7.19	3.64	6.97	1.03	11.45	1.593
PenShui shiplift	36	12.0	3.00	11.8	1.02	17.839	1.48
ShuiKou shiplift	75	34.0	2.20	29.5	1.16	42.19	1.24
TingZikou Shiplift	60.05	24.48	2.43	21.8	1.12	31.487	1.295
The second step of GouPitan shiplifts	36.2	15.8	2.30	15.5	1.02	20.57	1.465

the type of full balanced hoist vertical shiplifts is to increase the number and diameters of hoist wire ropes, which means to increase the weight of torque counterweight and the torsional rigidity of synchronizing shafts, and increase the longitudinal distance of hoist as much as possible.

4. Conclusions

This paper researches the two issues which closely relate to the safety of the type of the full balanced hoist vertical shiplifts, leakage and pitch stability of ship chambers, applying comprehensively the methods of combination of theory deduction, numeral computation, the application of results of model test and the summary of the experience of engineering design and operation, from which the conclusions are drawn:

(1) By theoretical analysis of leakage process, and considering it to be the accident of small probability, this paper puts forward concept of grading the full balanced hoist vertical shiplifts in safety, that is, the general grade and the special grade. The suggestions of the corresponding engineering measures have been proposed.

(2) This paper builds and compares several mathematic models, from simple to complicated, and derives a design formula for calculation of pitch stability of the ship chambers of the vertical shiplifts by the combination of theory and engineering practices, and propose the ways for improving the pitch stability of the type of the full balanced hoist vertical shiplifts.

(3) The research results of this paper have proved that the type of full balanced hoist vertical shiplifts is safe when correct and reasonable design is performed.

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